Mass Transport by Second Mode Internal Solitary Waves

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LONG-TERM GOALS

The overall scientific objective of the proposed effort is to improve our understanding of the propagation and mass transport of internal solitary waves (ISW), particularly mode-2 ISW, and their significance for coastal ocean processes. In recent years numerous observations of mode-2 ISW have been reported so that it appears that such waveforms may be more prevalent than previously thought. Large amplitude mode-2 solitary waves have unique properties, in particular they encompass regions of internal recirculation that enable mass transport over large distances. Transport of mass along a pycnocline can affect upper ocean mixing and distribution of biological and chemical constituents. Moreover, coherent ISW packets can have significant effects on the propagation and scattering of acoustic signals.

OBJECTIVES

The objectives of the current effort are to: (1) improve our fundamental understanding of mode-2 ISW mass transport including the effects of ambient shear; (2) characterize the three-dimensional mass transport from localized sources; and, (3) use the results to aid in the interpretation of ocean observations and ascertain the implications for ocean mixing and bio-chemical transport.

APPROACH

Increased understanding of mass transport will be achieved by a combined series of numerical simulations and scaled laboratory experiments focused on determining the extent and persistence of ISW mass transport.

The numerical simulations of mode-2 ISW (O.M. Knio, Duke Univ.) will be based on the Boussinesq model developed by Terez & Knio (1998) and recently extended by Salloum et al. (2012). The model integrates the mass and momentum conservation equations and simulates the motion of Lagrangian particles, used to characterize and quantify mass transport. Also modeled is the evolution of a passive

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scalar and of a Lagrangian particle field, both used to analyze mixing and to compare predictions to experimental dye measurements. The extended model will:

1. Account for the presence of current shear,

2. Extend the model so as to account for the 3D evolution of a mode-2 ISW,

3. Incorporate higher-order discretization that would enable efficient computations of ISW at higher Reynolds numbers in order to more accurately simulate ocean conditions.

The laboratory experiments (A. Brandt, JHU/APL) will extend earlier (Brandt, 2007) and more recent studies on ISW mass transport (Brandt et al., 2011) in the existing two-layer interfacial tank. Basic wavefield properties (amplitude, wavelength, etc.) are measured by imaging the evolution of the dye initially placed in the mixed generation region. Mass transport is determined by imaging the area of the dye included in the ISW bulge. Laser sheet imaging of fluorescent dye will be employed to ascertain the dynamics of the internal recirculation patterns in the large-amplitude ISW. PIV will also be employed to determine local velocities in the vicinity and within the ISW bulges. These studies will:

1. Investigate the efficiency of various mechanisms for ISW generation and mass transport to simulate the candidate ocean forcing conditions.

2. The effects of ambient shear flow on ISW generation/propagation process will be studied in the JHU/APL interfacial shear tunnel.

3. ISW mass transport and spreading in 3D, simulating the evolution of ISW in the coastal ocean, will be investigated in 3D (square) stratified tank, to provide an understanding of the extent of mass transport and a comparison to the 2D case.

WORK COMPLETED

This study was initiated mid-year in FY12. As a result limited work has been completed and results have yet to be determined.

The earlier numerical study on mode-2 ISW mass transport has been completed and published: Salloum, Knio & Brandt (2012). Preliminary experimental results have been presented at the APS DFD meeting: Brandt, et al. (2011) and manuscript for publication is in preparation.

A series of laboratory experiments using different mechanisms for ISW generation and mass transport (to simulate the candidate ocean forcing conditions) has been completed and analysis is in progress. The generation mechanisms investigated include:

- Mixed region release ("dam break") – simulating front/intrusion ISW generation

- Ocsillating mixer – simulating internal wave generated mixing

- Rotating paddle mixer – simulating internal wave instabilities

- Forced wedge displacement – simulating flow over a seamount.

On the computational side, our efforts have focused on:

- Extension of our previous model (Salloum et al., 2012) in order to account for the impact of shear on ISW, and implementation of the extended solver to characterize the impact of Richardson number on the evolution of mode-2 ISW and their mass transport properties; and,

- Formulation and development of a new, high-order primitive-variable Boussinesq solver that will be primary tool for analyze the behavior of ISW in three dimensional settings.

RESULTS

This study was initiagted mid-year in FY12. As a result limited work has been completed and results have yet to be determined.

The laboratory experiments using different mechanisms for ISW generation and mass transport have shown qualitatively significant differences in the amplitudes of the ISW and thus the potential for mass transport. Detailed analysis of these data is in progress.

A series of computational experiments has been conducted of the impact of Richardson number on the evolution ISW. The resulting database will be exploited to analyze the effect of shear on the mass transport properties of mode-2 ISW, and for the purpose of validating the newly-developed high-order pressure-based solver.

IMPACT/APPLICATIONS

Transport of mass along a pycnocline can affect upper ocean mixing and distribution of biological and chemical constituents. Coherent ISW packets can also have significant effects on the propagation and scattering of acoustic signals. The present fundamental investigation of mode-2 ISW can aid in interpretation of ocean observations of ISW and their mass transport effects.

TRANSITIONS

The results of this effort will be transitioned to Navy programs concerned with ocean wave dynamics and vehicle signatures.

RELATED PROJECTS

ONR Code 331 study of Body Generated Internal Waves. This study complements the present effort by relating basic oceanographic processes to those involving wave generation by Navy assets.

REFERENCES

Brandt, A. 2007 "Evolution of Mode-2 Solitary Internal Waves in a Stratified Shear Flow." Fifth International Symposium on Environmental Hydraulics (ISEH V), Tempe, Arizona, 4-7 December 2007, 6 pp.

Brandt, A. & Shipley, K.R, Salloum, M. & Knio, O.M. 2011 "Mass Transport by Large Amplitude

Internal Solitary Waves," 64th Annual Meeting of the Am. Phys. Society Division of Fluid Dynamics (DFD), 20-22 November 2011, Baltimore, MD.

Salloum, M., Knio, O.M., Brandt, A., "Numerical Simulation of Mass Transport in Internal Solitary Waves," Phys. Fluids, 24, 016602 (2012); doi: 10.1063/1.3676771.

Terez, D.E., Knio, O.M., "Numerical simulations of large-amplitude internal solitary waves", *J. Fluid Mech. 362,*53-82 (1998).

PUBLICATIONS

Salloum, M., Knio, O.M., Brandt, A., "Numerical Simulation of Mass Transport in Internal Solitary Waves," Phys. Fluids, 24, 016602 (2012); doi: 10.1063/1.3676771. [published, refereed]

HONORS/AWARDS/PRIZES

O. Knio was named Distinguished Professor on July 1, 2012.